Baryogenesis in Fresh inflation

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Abstract

I study the possibility of baryogenesis can take place in fresh inflation. I find that it is possible that violation of baryon number conservation can occur during the period out-of-equilibrium in this scenario. Indeed, baryogenesis could be possible in the range of times $(10^9 - 10^{12})$ $G^{1/2}$, before the thermal equilibrium is restored at the end of fresh inflation.

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Introduction: The idea of inflation is one of the most reliable concepts in modern cosmology [1–4]. It can solve the horizon and flatness problem in standard big bang cosmology and also provide us with the seeds of the large scale structure. The standard inflationary period proceeds while a scalar field called an inflaton slowly evolves along a sufficiently flat potential. The standard slow - roll inflation model separates expansion and reheating into

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two distinguished time periods. It is first assumed that exponential expansion from inflation places the universe in a supercooled second order phase transition. Subsequently thereafter the universe is reheated. Two outcomes arise from such a scenario. First, the required density perturbations in this cold universe are left to be created by the quantum fluctuations of the inflaton. Second, the scalar field oscillates near the minimum of its effective potential and produces elementary particles. Inflation has improved upon the scenario for generating a baryon excess in two ways. First, it has imposed the condition that the initial baryon asymmetry vanishes as a prediction of just as a convenient assumption. Second, has provided a maximum temperature below which the baryon generation process must take place. For standard inflation baryon number violation must take place at temperatures below the reheating temperature after inflation if our present universe is to end up with a non-zero baryon density. The picture of baryon generation which inflation give us is the following. When inflation ends, a scalar field which had been storing the energy density which drove inflation in the form of a cosmological constant is suddenly released from a meta-stable configuration and it rapidly proceeds to the minimum of its potential energy. As it approaches the minimum the potential energy of the meta-stable state is transferred to kinetic energy and the field value oscillates around the minimum of the potential. These field oscillations are completely equivalent to a coherent state of the particles corresponding to the scalar field. The next step is that these particles decay, or equivalently, that field oscillations are damped by the production of other particles which are coupled to the oscillating field. This accomplishes the reheating of the universe [5]. Baryon number is generated when the temperature of the universe dips below the mass of some suitable particle. There is a temporary loss of equilibrium when that particle cannot decay quickly enough to reduce its density in response to the rapidly cooling universe. The particle being discussed must have decay modes which violate both CP and baryon number conservation. There are very good reasons to suspect that GUT baryogenesis does not occur if this is the way reheating happens. The main reason is that density and temperature fluctuations observed in the present universe require the inflaton potential to be extremely flat. This means that the

couplings of the inflaton field to the other degrees of freedom cannot be too large, since large couplings would induce large loop corrections to the inflaton potential, spoiling its flatness. As a result, the radiation temperature is expected to be smaller than 10^{14} GeV by several orders of magnitude [6].

An interesting idea called preheating was introduced more recently [7]. When the inflaton field oscillates around the minimum of the potential the Klein-Gordon equation for the modes can be cast in the form of a Mathieu equation. A crucial observation for baryogenesis is that particles with mass larger than that of the inflaton may be produced during preheating [8].

Recently a new model of inflation called *fresh inflation* was proposed [9]. This one has the following characteristics:

(a) The universe begins from an unstable primordial matter field perturbation with energy density nearly M_p^4 and chaotic initial conditions. Initially the universe there is no thermalized $[\rho_r(t = t_0) = 0]$. Later, the universe describes a second order phase transition, and the inflaton rolls down towards its minimum energetic configuration. (b) Particles production and heating occur together during the rapid expansion of the universe, so that the radiation energy density grows during fresh inflation ($\dot{\rho}_r > 0$). The Yukawa interaction between the inflaton field and other fields in a thermal bath lead to dissipation which is responsible for the slow rolling of the inflaton field. So, the slow-roll conditions are physically justified and there are not a requirement of a nearly flat potential in fresh inflation. (c) There is no oscillation of the inflaton field around the minimum of the effective potential due to the strong dissipation produced by the Yukawa interaction ($\Gamma \gg H$). This fact also provides thermal equilibrium in the last phase of fresh inflation.

In this work I study baryogenesis in fresh inflation. During the early period of fresh inflation (when $\Gamma \ll H$) there is not thermal equilibrium, but after $t > t_E$ the thermal equilibrium es restored (once the condition $\Gamma \gg H$ is fullfiled). The main subject of this paper is to study the possibility that baryon asymmetry can take place during the period before thermal equilibrium is restored in fresh inflation.

Review of Fresh Inflation: I consider a Lagrangian for a ϕ-scalar field minimally coupled

to gravity, which also interacts with another ψ-scalar field by means of a Yukawa interaction,

$$\mathcal{L} = -\sqrt{-g}\left[\frac{R}{16\pi G} + \frac{1}{2}g^{\mu\nu}\phi_{,\mu}\phi_{,\nu} + V(\phi) + \mathcal{L}_{int}\right], \tag{1}$$

where $g^{\mu\nu}$ is the metric tensor, g is its determinant and R is the scalar curvature. The interaction Lagrangian is given by $\mathcal{L}_{int} \sim -g^2\phi^2\psi^2$, where ψ is a scalar field in the thermal bath. Furthermore, the indices μ, ν take the values $0, .., 3$ and the gravitational constant is $G = M_p^{-2}$ (where $M_p = 1.2 \times 10^{19}\ GeV$ is the Planckian mass). The Einstein equations for a globally flat, isotropic, and homogeneous universe described by a Friedmann-Robertson-Walker metric $ds^2 = -dt^2 + a^2(t)dr^2$ are given by

$$3H^2 = 8\pi G\left[\frac{\dot\phi^2}{2} + V(\phi) + \rho_r\right], \tag{2}$$

$$3H^2 + 2\dot H = -8\pi G\left[\frac{\dot\phi^2}{2} - V(\phi) + \rho_r\right], \tag{3}$$

where $H = \frac{\dot a}{a}$ is the Hubble parameter and a is the scale factor of the universe. The overdot denotes the derivative with respect to the time. On the other hand, if $\delta = \dot\rho_r + 4H\rho_r$ describes the interaction between the inflaton and the bath, the equations of motion for ϕ and ρ_r are

$$\ddot\phi + 3H\dot\phi + V'(\phi) + \frac{\delta}{\dot\phi} = 0, \tag{4}$$

$$\dot\rho_r + 4H\rho_r - \delta = 0. \tag{5}$$

As in a previous paper [9], I will consider a Yukawa interaction $\delta = \Gamma(\theta)\ \dot\phi^2$, where $\Gamma(\theta) = \frac{g_{eff}^4}{192\pi}\theta$ [13] and $\theta \sim \rho_r^{1/4}$ is the temperature of the bath. If $p_t = \frac{\dot\phi^2}{2} + \frac{\rho_r}{3} - V(\phi)$ is the total pressure and $\rho_t = \rho_r + \frac{\dot\phi^2}{2} + V(\phi)$ is the total energy density, the parameter $F = \frac{p_t+\rho_t}{\rho_t}$ which describes the evolution of the universe during inflation [11] is

$$F = -\frac{2\dot H}{3H^2} = \frac{\dot\phi^2 + \frac{4}{3}\rho_r}{\rho_r + \frac{\dot\phi^2}{2} + V} > 0. \tag{6}$$

When fresh inflation starts (at $t = G^{1/2}$), the radiation energy density is zero, so that $F \ll 1$.

I will consider the parameter F as a constant. From the two equalities in eq. (6), one obtains the following equations:

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$$\dot{\phi}^2 \left(1 - \frac{F}{2}\right) + \rho_r \left(\frac{4}{3} - F\right) - F\, V(\phi) = 0, \tag{7}$$

$$H = \frac{2}{3 \int F\, dt}. \tag{8}$$

Furthermore, because of $\dot{H} = H'\dot{\phi}$ (here the prime denotes the derivative with respect to the field), from the first equality in eq. (6) we obtain the equation that describes the evolution for ϕ,

$$\dot{\phi} = -\frac{3H^2}{2H'}F, \tag{9}$$

and replacing eq. (9) in eq. (7), the radiation energy density can be described as functions of V, H and F [9]

$$\rho_r = \left(\frac{3F}{4 - 3F}\right) V - \frac{27}{8} \left(\frac{H^2}{H'}\right)^2 \frac{F^2(2 - F)}{(4 - 3F)}. \tag{10}$$

Finally, replacing eqs. (9) and (10) in eq. (2), the potential can be written as a function of the Hubble parameter and F (which is a constant)

$$V(\phi) = \frac{3}{8\pi G} \left[\left(\frac{4 - 3F}{4}\right) H^2 + \frac{3\pi G}{2}F^2 \left(\frac{H^2}{H'}\right)^2\right]. \tag{11}$$

Fresh inflation was proposed for a global group $O(n)$ involving a single n-vector multiplet of scalar fields ϕ_i [12], such that making $(\phi_i\phi_i)^{1/2} \equiv \phi$, the effective potential $V_{eff}(\phi, \theta) = V(\phi) + \rho_r(\phi, \theta)$ can be written as

$$V_{eff}(\phi, \theta) = \frac{\mathcal{M}^2(\theta)}{2}\phi^2 + \frac{\lambda^2}{4}\phi^4, \tag{12}$$

where $\mathcal{M}^2(\theta) = \mathcal{M}^2(0) + \frac{(n+2)}{12}\lambda^2\theta^2$ and $V(\phi) = \frac{\mathcal{M}^2(0)}{2}\phi^2 + \frac{\lambda^2}{4}\phi^4$. Furthermore, $\mathcal{M}^2(0) > 0$ is the squared mass at zero temperature, which is given by $\mathcal{M}_0^2$ plus renormalization counterterms in the potential $\frac{1}{2}\mathcal{M}_0^2(\phi_i\phi_i) + \frac{1}{4}\lambda^2(\phi_i\phi_i)^2$ [12]. I will take into account the case without symmetry breaking, $\mathcal{M}^2(\theta) > 0$ for any temperature θ, so that the excitation spectrum consists of n bosons with mass $\mathcal{M}(\theta)$. The effective potential (12) is invariant under $\phi \rightarrow -\phi$ reflections and n is the number of created particles due to the interaction of ϕ with the particles in the thermal bath, such that [9]

$$(n + 2) = \frac{2\pi^2}{5\lambda^2} g_{eff} \frac{\theta^2}{\phi^2}, \tag{13}$$

because the radiation energy density is given by $\rho_r = \frac{\pi^2}{30}, g_{eff}\theta^4$, where g_{eff} denotes the effective degrees of freedom of the particles and it is assumed that ψ has no self-interaction. A particular solution of eq. (11) is

$$H(\phi) = 4\sqrt{\frac{\pi G}{3(4 - 3F)}} \, \mathcal{M}(0) \, \phi, \tag{14}$$

where the consistence relationship implies: $\lambda^2 = \frac{12\pi GF^2}{(4-3F)} \mathcal{M}^2(0)$ [9]. From eq. (8), and due to $H = \dot{a}/a$, one obtains the scale factor as a function of time

$$a(t) \sim t^{\frac{2}{3F}}. \tag{15}$$

The number of e folds $N = \int_{t_s}^{t_e} H(t)dt$ (t_s and t_e are the time when inflation start and ends) is given by $N = \frac{2}{3F}\ln(t)\Big|_{t_s}^{t_e}$. With Planckian unities ($G^{-1/2} \equiv M_p = 1$) inflation starts when $t_s = G^{1/2} = 1$. Hence, for $t_e \simeq 10^{13} \, G^{1/2}$, one obtains $N > 60$ for $F < 1/3$. So, the condition $F < 1/3$ assures the slow-rolling of the inflaton field during fresh inflation. So, fresh inflation solve the problem of warm inflationary scenarios considered in [10]. Taking $g_{eff} \simeq 10^2$, $\mathcal{M}^2(0) = 10^{-12} \, \mathrm{M_p^2}$, and $t_e \simeq 10^{13}G^{1/2}$ one obtains the number of created particles at the end of fresh inflation $n_e \simeq 10^{13}$. Furthermore, the time evolution of the inflaton is given by $\phi(t) = \lambda^{-1}t^{-1}$ [9].

Baryogenesis in Fresh inflation: If the reheat temperature is sufficiently high, then baryogenesis can proceed as it does in the standard cosmology, through the out-of-equilibrium decays of superheavy bosons whose interactions violate B, C and CP conservation [15]. As usual, ϵ is related to the branching ration of ϕ into channels which have net baryon number, and the C, CP violation in the B-nonconserving decay modes. For simplicity suppose that only two decay channels have net baryon number equal to B_1 and B_2, then $\epsilon \simeq (B_1 - B_2)(r_1 - \bar{r}_1)(r_1 + \bar{r}_2)$, where r_i ($\bar{r}_i$) is the branching ration into channel i ($\bar{i}$). The C, CP-violating effects involve higher - order loop corrections $(r_1 - \bar{r}_1) \leq O(\alpha) \geq 10^{-2}$, where α is the coupling strength of the particle exchanged in the loop.

For the values of the parameters here adopted the thermal equilibrium holds for $t >$ $t_E \simeq 10^{12}$ G$^{1/2}$, so that baryogenesis must take place before it. If baryon number is not conserved there is no reason for the proton to be stable and in fact, most theories which can produce a baryon asymmetry also predict a finite lifetime for the proton. Experiments now constrain this lifetime to be longer than 10^{32} years [14]. This suggests that the energy scale associated with baryon number violating processes is greater than 10^{11} GeV but remains below of the 10^{16} GeV. Indeed, if the temperature of the universe grows until values of temperature greater than θ_B before the thermal equilibrium is restored, fresh inflation could give violation of baryon number conservation. During fresh inflation the entropy density is $s \simeq \frac{2\pi^2}{45}g_{eff}\theta^3$. If the decay of each ϕ-boson on average a net baryon number density ϵ, then the net baryon number density produced by the ϕ-decay in unstable bosons is $n_B \simeq \epsilon n_\phi$, where $n_\phi \simeq \frac{\rho_r}{\mathcal{M}(\theta)}$, such that

$$n_B \simeq \epsilon \frac{(n+2)\lambda^2\theta^2\phi^2}{12\sqrt{\mathcal{M}^2(0) + \frac{(n+2)}{12}\lambda^2\theta^2}}. \tag{16}$$

But the important relationship here is n_B/s, which takes the form

$$\frac{n_B}{s} \simeq \frac{45\epsilon(n+2)\lambda^2\phi^2}{24\pi^2 g_{eff}\theta\sqrt{\mathcal{M}^2(0) + \frac{(n+2)}{12}\lambda^2\theta^2}}. \tag{17}$$

If the temperature is given by [9]

$$\theta(t) \simeq \frac{192\pi}{g_{eff}^4}\mathcal{M}^2(0)\, t, \tag{18}$$

the time for which the condition to baryogenesis take place $n_B/s \simeq 10^{-10}$ [15] (I call it t_B), will be

$$t_B \simeq \frac{22}{\epsilon}, \tag{19}$$

where we have taken $\mathcal{M}^2(0) = 10^{-12}$ M$_{\rm p}^2$ and $g_{eff} = 10^2$. Notice that t_B is smaller than the time when the thermal equilibrium is restored $t_E \simeq 10^{12}$ G$^{1/2}$, for

$$\epsilon < 10^{-11}, \tag{20}$$

which agree with the expected values. Finally, the minimum radiation temperature needed to baryogenesis take place (of the order of 10^{-8} G$^{-1/2}$) is obtained for $t_B \simeq 10^9$ G$^{1/2}$, which is smaller than the equilibrium temperature t_E. This implies the possibility of violation of baryon number conservation during the out-of-equilibrium period of fresh inflation. Notice that when the thermal equilibrium is restored the temperature of the universe is of the order of $\theta_E \simeq 10^{-6}$ G$^{-1/2}$, which is in the permited range of temperatures [$(10^{-8} - 10^{-3})$ G$^{-1/2}$] for baryogenesis can take place. In other words, with the choice of parameters here worked ($\mathcal{M}^2(0) = 10^{-12}$ G^{-1} and $g_{eff} = 10^2$), the fresh inflationary model predicts the possiblity of violation for baryon number conservation in the range of times $(10^9 - 10^{12})$ G$^{1/2}$.

To summarize, the conditions needed to give rise to a baryon asymmetry have long been recognized. They are (i) violation of baryon number conservation (ii) violation of CP invariance and (iii) temporary loss of thermal equilibrium. Inflation requires violation of baryon number conservation, which suggests that the proton is unstable. This provides us with a bleak picture of a future universe devoid of matter an ever decreasing photon density. In this paper I have showed that baryogenesis can take place during fresh inflation before the thermal equilibrium is restored. This is a very attractive prediction of fresh inflation which shows an important difference with respect to another models of inflation where baryogenesis is produced at the end of the inflationary phase [16,17]. In the framework of fresh inflation, other interesting variants such preheating [7] or the Afflek-Dine mechanism [18] cannot occur due to there are no oscillation of the inflaton field at the end of fresh inflation. Finally, baryogenesis appears to be very difficult in low-energy unification scenarios and in supersymmetric unified models with dimension-5 operators that violate B conservation. However, while it is difficult to generate a baryon asymmetry at low temperature, it is not impossible. A scenario based on $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ where the X-bosons are the right-handed neutrino and $M = 10^4$ GeV has been discussed in [19].

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